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Precise Measurement of the Tau Lifetime

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The τ lifetime was measured with the Mark II vertex detector at the storage ring PEP. $\tau_\tau = (3.20 \pm 0.41 \pm 0.35) \times 10^{-13}$ sec was found, which agrees well with e-μ-τ universality.

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The electron and muon couple to the charged weak current with identical strengths to a high degree of accuracy.[1] A measurement of the τ lifetime tests whether it too couples with the universal Fermi strength. Several experiments[2-4] have measured the average decay length of τ leptons which have been pair produced in e^+e^- interactions and find the lifetime to be compatible with e-μ-τ universality within large statistical and systematic errors. Since the τ lifetime provides an exacting test of the standard-model assumptions,[5] it is important to measure it to high accuracy. In this Letter we describe a new measurement[6] of the τ lifetime made with a high-precision vertex detector in conjunction with the Mark II detector at the Stanford Linear Accelerator Center e^+e^- storage ring PEP. This device measures the decay length with a resolution comparable to the expected decay length (680 μm at the PEP center-of-mass energy 29 GeV), in contrast to the previous measurements which had resolutions about 5 times worse.

The Mark II vertex detector[7] is a high-precision, cylindrical drift chamber located between a beryllium beam pipe and the central Mark II tracking chamber. The beam pipe, which is 0.6% of a radiation length thick, also serves as the inner wall of the chamber so as to minimize multiple Coulomb scattering. The chamber is 120 cm long and has been seven axial layers of drift cells, four of which are just outside the beam pipe at an average radius of 11.2 cm, with the remaining three at 31.2 cm. The drift cell radius is 0.53 cm throughout the chamber. The average spatial resolution in hadronic events is 110 μm per layer. Tracks which have been extrapolated to the interaction point are measured with an accuracy of $\sigma_T(\mu\text{m}) = \{(95)^2 + [95/P(\text{GeV}/c)]^2\}^{1/2}$ in the plane perpendicular to the beams, the second term arising from multiple Coulomb scattering in the beam pipe. The vertex detector is used in conjunction with the central drift chamber to measure charged-particle momenta. The central chamber has sixteen cylindrical layers of sense wires at radii between 41 and 145 cm. Six layers are parallel to the incident beams and the other ten are ±3° relative to the incident beams. Both chambers operate inside a 2.3 kG solenoidal magnetic field. The momentum resolution of the vertex-detector–central-chamber combination is $\Delta P/P = [(0.02)^2 + (0.011P)^2]^{1/2}$ when tracks are not constrained to pass through the luminous region. Just outside the solenoid coil there are eight lead–liquid-argon shower counters which detect photons over 65% of the solid angle. The Mark II detector is discussed more thoroughly by Schindler *et al.*[8]

The data presented here correspond to an integrated luminosity of 41 pb^{-1}. All the data were taken at a center-of-mass energy of 29.0 GeV.

We measure the τ lifetime by measuring the displacement of its three-prong decay vertices from the point where the e^+ and e^- beams collide. Since the τ is produced with the known beam energy, the average displacement is proportional to the lifetime.

Tau production is so distinctive at high energies that events can be selected with very little background. We find three-prong τ decays by choosing charge-balanced two-jet events with $1+3$ or $3+3$ charged-prong topologies. We require that there be at least one three-particle combination with unit charge and an invariant mass between 0.7 GeV/c^2 and 1.5 GeV/c^2 calculated assuming the prongs to be pions. To eliminate beam-gas backgrounds and suppress contamination from two-photon τ-pair production, we demand that the total charged plus neutral energy in the event exceed 25% of the center-of-mass energy and that the energy of the three-particle combination exceed 3.0 GeV. We suppress hadronic backgrounds by requiring the invariant mass of the charged and neutral particles in each jet be less than 2.0 GeV/c^2. To guard against radiative Bhabha scattering, we require the total charged energy in the event to be less than 85% of the center-of-mass energy, and the three-particle invariant mass calculated under the assumption that each prong is an electron to be greater than 300 MeV/c^2. Using Monte Carlo methods, we estimate that (4 ± 2)% of the selected decays are misidentified hadrons, and (4 ± 1)% of the events are τ pairs produced via the two-photon mechanism. Backgrounds from radiative QED events and beam-gas processes are negligible.

A total of 621 three-prong decays are selected with the above criteria. We next impose several tracking-quality cuts. Each of the three tracks must extrapolate to within 5 mm of the beam position in the plane (x-y) perpendicular to the beams and to within 5 cm of the vertex formed from all the tracks in the event in the direction along the beams. To minimize both scattering and decay probabilities, we require each track to have momentum greater than 400 MeV/c. We further require that each track has been measured in at least two of the inner vertex-detector layers, and at least one of the outer layers. Finally, each track fit must have an overall χ^2 per degree of freedom less than 5, and the χ^2 per degree of freedom from the vertex detector must be less than 4. This leaves 185 decays suitable for vertexing.

The most probable decay length is determined from the position of the decay vertex, the beam position, the τ direction, and the errors in these quantities.

We find the decay-vertex position and its errors in the x-y plane from the parameters of the three particle trajectories with a χ^2 minimization procedure. Requiring the vertex χ^2 to be less than 15 for three degrees of freedom leaves 180 decays. This χ^2 distribution is somewhat broader than we expect from our known tracking errors, and we have therefore increased our estimate of the vertex-position errors by 10%. The uncertainties in this procedure are included in the systematic errors discussed below.

The τ direction is approximated quite closely by the direction of the three-pion system since that system is slow in the τ rest frame, and the τ is highly relativistic in the laboratory.

We measure the beam position on a run-by-run basis by finding the position which minimizes the distance of closest approach for an ensemble of tracks. In a typical 2-h storage-ring fill, we measure the average beam position within 20 μm vertically and 50 μm horizontally. We measure the rms beam size to be 65 ± 15 μm vertically and 480 ± 10 μm horizontally. The beam position is stable during a fill, and is usually constant for large blocks of data. Beam-position monitors sensitive to 20-μm shifts in the beam position flagged the few runs where steering changes occurred midrun, and runs with excessive beam motion were ignored. We have checked the beam-position determination by vertexing hadronic events, and we find good agreement between the average vertex position and the beam position.

The projected decay length is given in terms of the decay-vertex position relative to the beam position (x_v, y_v), the sum of the beam and vertex error matrices σ_{ij}, and the two-dimensional τ direction cosines t_i by the expression

$$l_p = \frac{x_v\,\sigma_{yy}\,t_x + y_v\,\sigma_{xx}\,t_y - \sigma_{xy}(x_v\,t_y + y_v\,t_x)}{\sigma_{yy}\,t_x^{\,2} + \sigma_{xx}\,t_y^{\,2} - 2\sigma_{xy}\,t_x\,t_y}\,.$$

The decay length is then $l = l_p/\sin\theta$, where θ is the angle between the three-pion direction and the beam direction. The resolution in the decay length depends on the opening angles, track momenta, and orientation of each decay. It varies between 500 and 1800 μm for most decays and averages 1100 μm. After requiring the resolution to be less than 1700 μm, we are left with 156 decays for study. Figure 1 shows their decay-length distribution. The mean of the distribution is 679 μm, and its shape is asymmetric, showing the expected long-lifetime tail.

We use a maximum-likelihood fit to determine the average decay length. The fitting function is the convolution of an exponential decay distribu-

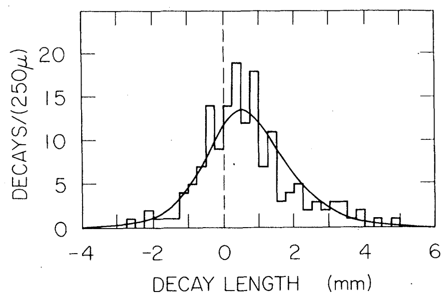

FIG. 1. Measured τ decay lengths. The solid curve is the best fit to the data described in the text.

tion with a Gaussian resolution function whose width σ_l is calculated event by event. The result of the fit depends on both the width and the potential offset of the resolution function, and so we have checked those quantities with two different methods. The first is from a study of "pseudotau decays" in hadronic events. For this study, we select three-track combinations in hadronic events which pass our tracking criteria and which have kinematic properties like the three-pion τ decays. We systematically exclude any track which may come from $K_s{}^0$ decay and the highest-momentum track in a jet to suppress contamination from events with secondary vertices. Figure 2(a) shows the decay-length distribution for the pseudo-tau decays. This distribution is peaked near zero decay length with some excess of events at positive decay lengths. The fitted mean decay length is 72 ± 38 μm. We have simulated this measurement with Monte Carlo techniques and find that the presence of charm and bottom decays give decay lengths in the range 50 to 150 μm, depending on the D^+/D^0 ratio and the lifetime of bottom hadrons. This confirms that there is little if any offset in our resolution function. Figure 2(b) shows the distribution of decay lengths of the pseudo-tau events divided by their errors. The distribution is represented nicely by a unit-width Gaussian function, which is also shown in the figure. A fit confirms that our calculation of the width of the resolution function is correct to the 5% level. Our second method for checking the resolution function is to fit the observed τ decay-length distribution for the width or offset of the resolution function in addition to the decay length. We find the offset to be consistent with zero, 83 ± 128 μm; the factor which scales the width of the resolution function is 1.00 ± 0.085. So the data are consistent with our choice of resolution function.

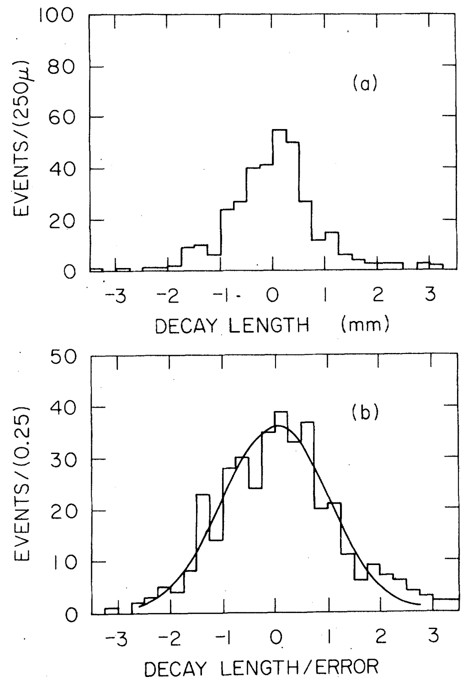

FIG. 2. (a) Measured decay lengths for "pseudo-τ" decays; (b) decay length divided by its calculated error for pseudo-τ decays. The solid curve is a unit-width Gaussian function, normalized to the data between $-2.5 \leq l/\sigma \leq 2.5$.

The result of the maximum-likelihood fit to the τ decay-length distribution is 705 ± 87 μm, where the error is statistical only. The fit is shown superimposed on the data in Fig. 1, and describes the data adequately. Correcting the decay length for backgrounds (+30 μm) and noting that initial-state radiation lowers the average τ energy from 14.5 to 13.8, we find $\tau_\tau = (3.20 \pm 0.41) \times 10^{-13}$ sec.

We have investigated several potential sources of systematic error. The first is a measurement bias which comes about because the opening angles of the decay are differentially larger when the vertex position has fluctuated toward long decay lengths than when it has fluctuated toward short decay lengths. Larger opening angles result in smaller vertex errors, and consequently more weight in the fit for the longer decay lengths. In previous determinations of τ decay lengths, ~250-μm corrections were made to account for the bias. It has been reduced to the 25-μm level in this experiment by the improvements in tracking resolution and the reduction of multiple Coulomb scattering. Secondly, we have checked the accuracy of the analysis technique with Monte Carlo–simulated raw data. The simulation included pion and kaon decay, photon conversions, nuclear absorption and scattering, and multiple Coulomb scattering in the beam pipe and wires of the vertex detector, and gives a good representation of the data. About 1000 decays were generated for each of three lifetimes, and then analyzed with the same programs used to analyze the actual data. The average decay lengths generated were 0, 629, and 1327 μm; the respective fitted values were 48 ± 36, 609 ± 35, and 1252 ± 56 μm. Finally, we have considered how errors in the various quantities essential to the analysis induce errors in the decay length. The uncertainties in the width (±7%) and offset (± 50 μm) of the resolution function each lead to uncertainties in the fitted decay length of ±35 μm. Reasonable variations in the shape of the resolution function can change the result by ±30 μm. The uncertainty in the background correction is ±15 μm. The result is insensitive to small changes in the estimated beam position and width. Altogether, including these and the other uncertainties in the analysis, we estimate the systematic error to be 80 μm.

In conclusion, we have measured the τ lifetime to be $\tau_\tau = (3.20 \pm 0.41 \pm 0.35) \times 10^{-13}$ sec, where the first error is statistical and the second is systematic. This value is consistent with previous measurements, and is in good agreement with the lifetime expected from e-μ-τ universality,

$$\tau_\tau = \tau_\mu (m_\mu / m_\tau)^5 B_e = 2.8 \pm 0.2 \times 10^{-13} \text{ s},$$

where τ_μ (m_μ) is the muon lifetime (mass) and B_e is the τ branching ratio into $e\nu\bar{\nu}$.[9]

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